# High Energy Density Science and Ion Beams

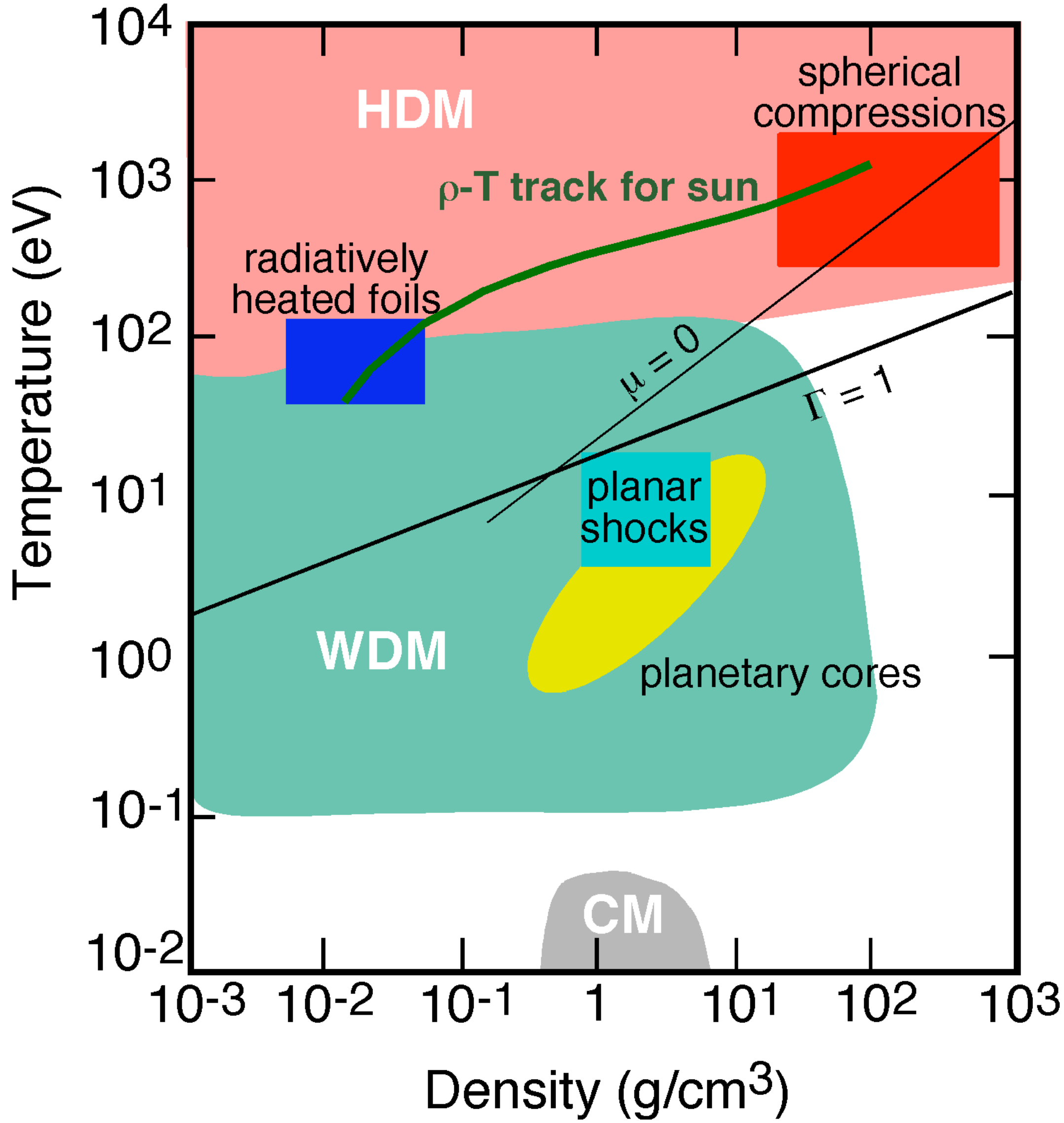
- Regimes and Physical processes of interest
- Discuss what is being done currently (Now)
- What will be done with current sources (Soon)
- What the future will look like (Later)

Richard W. Lee   October, 2004

# High Energy Density matter is interesting because it occurs widely

- **Hot Dense Matter (HDM) occurs in:**
  - Supernova, stellar interiors, accretion disks
  - Plasma devices: laser produced plasmas, Z-pinches
  - Directly and indirectly driven inertial fusion experiments
- **Warm Dense Matter (WDM) occurs in:**
  - Cores of large planets
  - Systems that start solid and end as a plasma
  - X-ray driven inertial fusion experiments

**Hydrogen phase diagram**

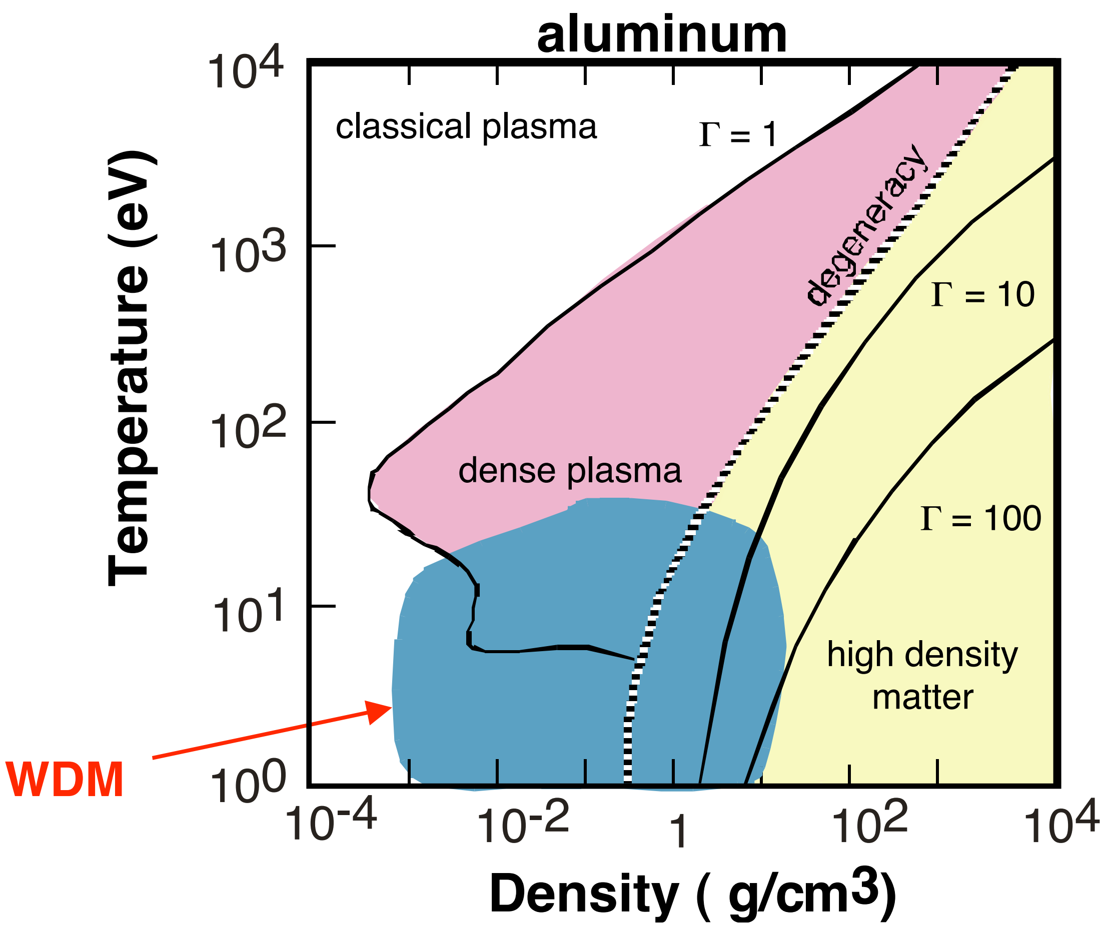


# Heavy ion beams could uniquely create matter at extreme conditions

- Emphasize the WDM part of HED regime
- Heavy ion beams have a decided advantage:
  - Relatively large sample sizes ($mm^3$)
  - More uniform conditions
  - Achieve high entropy at high density
  - Extreme conditions persist for long times
  - Repetition rates can be high
- In contrast, optical laser-based experiments in WDM regime have:
  - smaller volumes, larger gradients, shorter lifetimes, and lower repetition rates

# Defining the Warm Dense Matter regime

- WDM is that region in temperature-density space that is:
  1) Not described as normal condensed matter, i.e., T ~ 0
  2) Not described by weakly coupled plasma theory



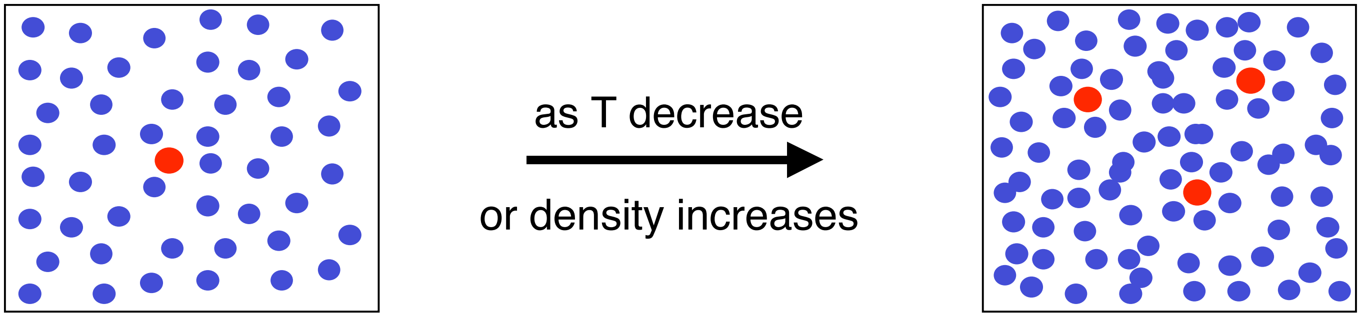

- $\Gamma$ is the strong coupling parameter, the ratio of the interaction energy between the particles, $V_{ii}$, to the kinetic energy, T

- $$\Gamma = \frac{V_{ii}}{T} = \frac{Z^2 e^2}{r_o T}$$

  where $r_o \propto \dfrac{1}{\rho^{1/3}}$

# From the point of view of a plasma the defining concept is coupling

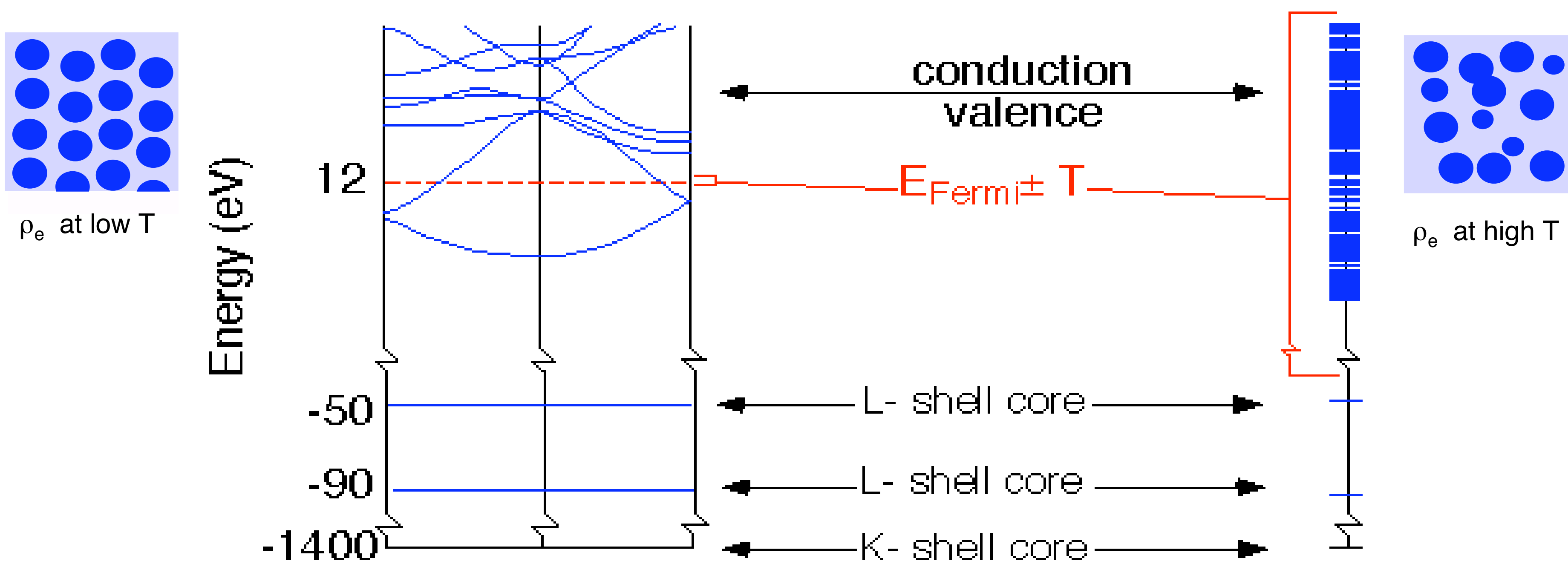
- Weakly couple plasmas are easy
  - The plasma can be seen as a separate point charges
  - Then the plasma is a bath in which all particles are treated as points - even particles with structure (e.g., atoms)




- But, when either $\rho$ increases or T decreases $\Gamma > 1$:
  - Particle correlations become important
  - Ionization potentials are depressed
  - Energy levels shift

# WDM is defined for condensed matter by temperature relative to the Fermi energy

- Fermi energy, $E_{Fermi}$, is the maximum energy level of an $e^-$ in cold condensed matter
- When $T << E_{Fermi} = T_{Fermi}$ standard condensed matter methods work
- When $T \sim T_{Fermi}$ one gets excitation of the core
  - Ion - $e^-$ correlations change and ion-ion correlations give short and long range order



# Research into WDM is in its infancy, so there is much to do

- WDM part of High Energy Density regime:
  - $E/V \sim 10^{11}$ ergs/cm$^3$
  - $T \sim 0.5 – 20$ eV
  - $\rho \sim 10^{-3} – 10$ g/cm$^3$
  - P ~ kbar – Mbar

- Research relevant for these extreme conditions:
  - Equation of state (EOS)
  - Critical points
  - Strongly coupled plasmas
  - Atomic physics
  - Transport properties: conductivity, opacity…
  - Plasma phase transitions

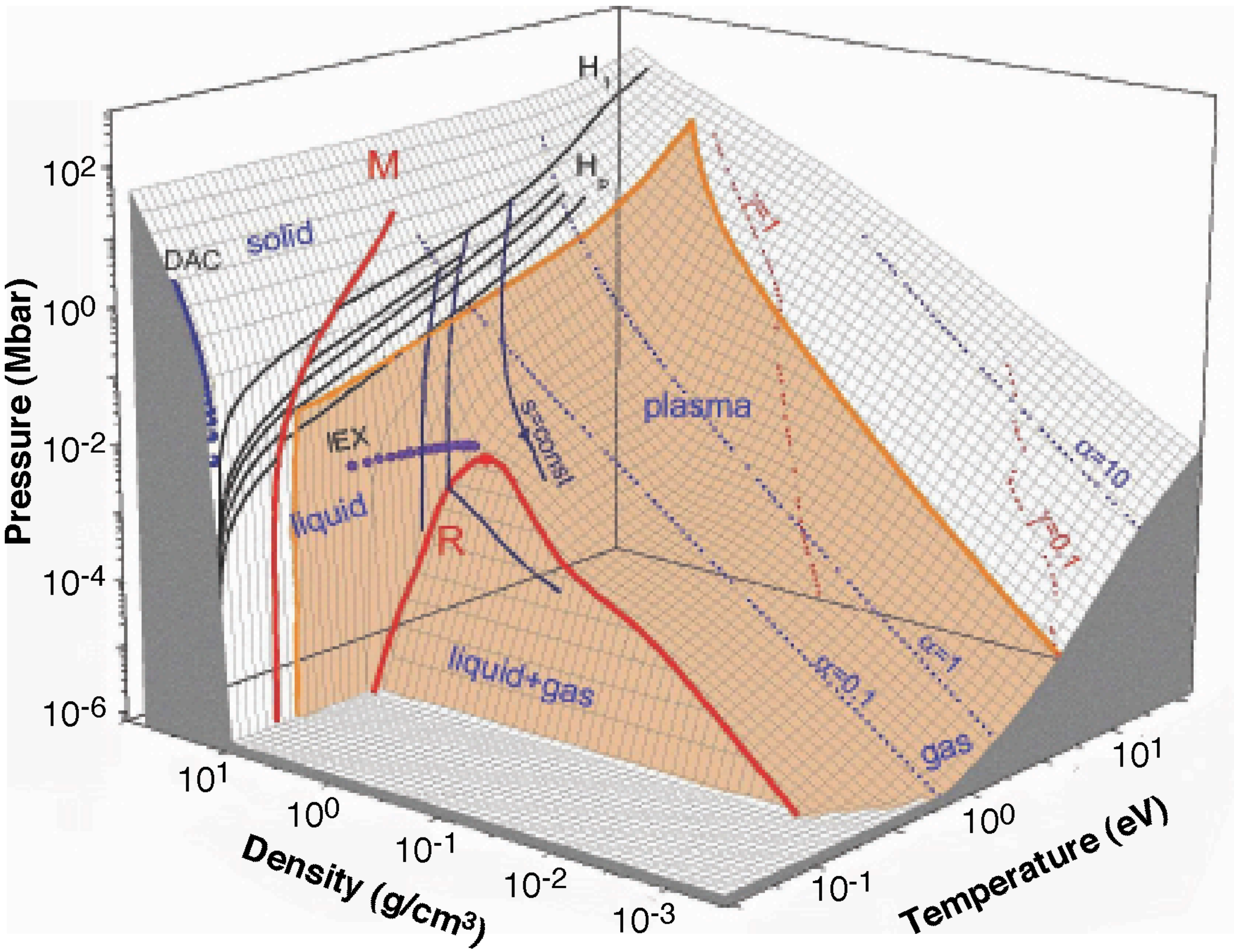
## Problem is not to create the WDM; but, to create it so that it can be studied

- Deposition of substantial energy in a short time leads to large gradients in temperature and $\rho$
  - Solid-vacuum interfaces expand rapidly
- Effort in *most* cases is to create matter that can be quantified
  - Measurements of temperature, densities ($n_e$, $n_i$, $\rho$), composition
  - Measurements of pressure, flow, uniformity
  - Measurements of constitutive properties
    - Shocks, turbulence, material mixing, etc. cause serious problems
- In other cases one tries to simulate an integral result , e.g, astrophysical process
- ***Again, Heavy ion beams represent a very attractive capability***

# WDM created by isochoric heating then isentropic expansion samples phase space

- Ion beam isochoric heating / isentropic expansion
- Principal ($H_1$) and porous ($H_p$) Hugoniots shock compression experiments
- Studied release isentropes (S)
- Isobaric expansion (IEX)
- Ionization degree ($\alpha$) and non-ideality parameter ($\gamma$) are shown

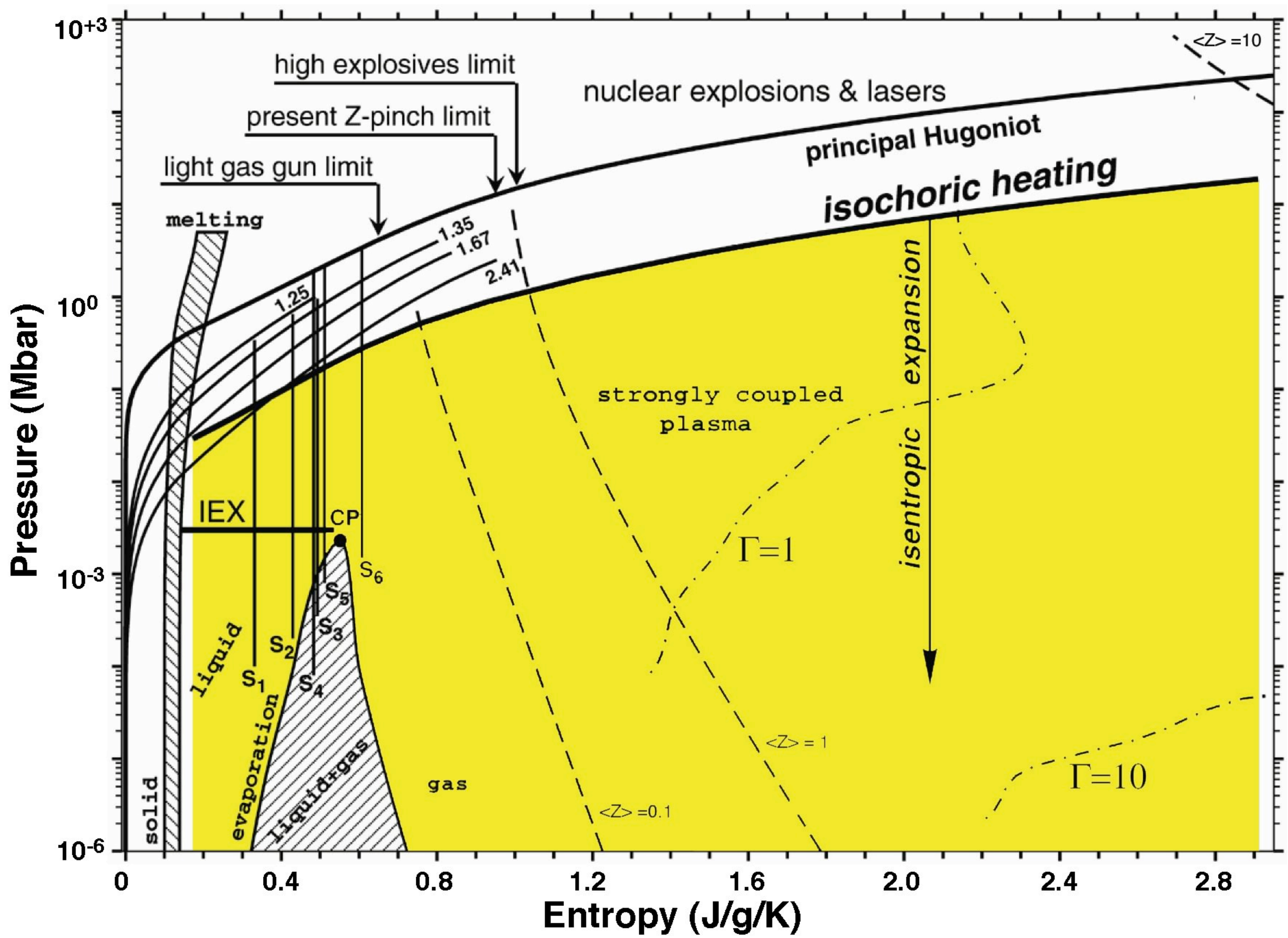
## Pb phase diagram



# WDM created by isochoric heating then isentropic expansion samples phase space

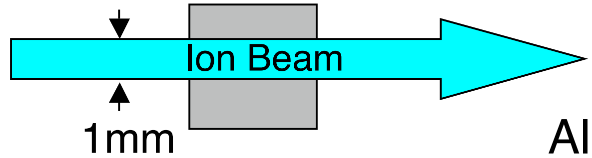
- Ion beam isochoric heating / isentropic expansion
- Principal and porous Hugoniots shock compression experiments
- Studied release isentropes (S)
- Isobaric expansion (IEX)
- Ionization degree (<Z>) and non-ideality parameter (Γ) are shown

## Pb phase diagram

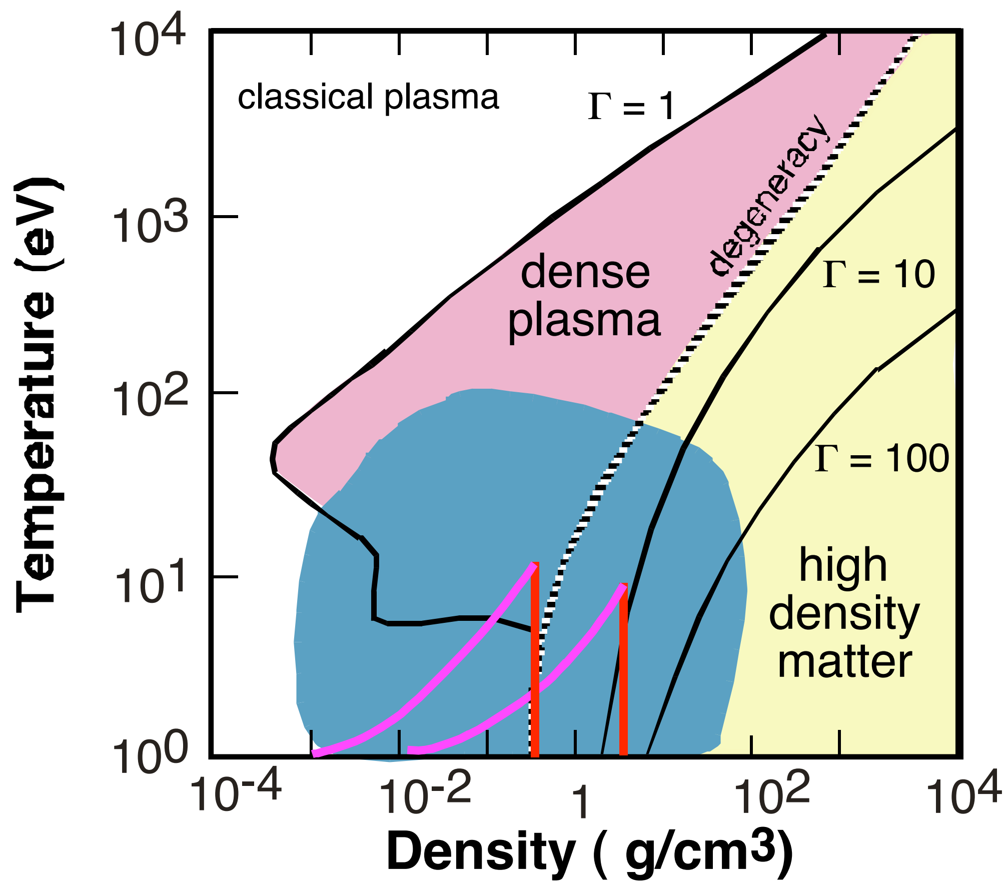


# WDM created by isochoric heating then isentropic expansion for the Al phase space

- Concept is straightforward




Al ρ-T phase diagram




- Ion beam can heat matter rapidly and uniformly to create:
  - Isochores (constant ρ)
  - Isentropes (constant entropy)

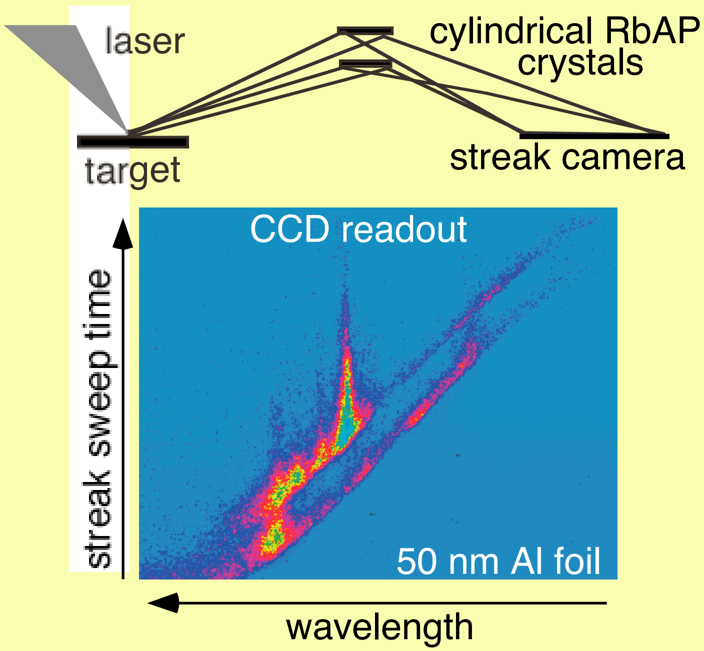
- Using underdense foams allows more complete sampling
  - Isochores (constant ρ)
  - Isentropes (constant entropy)

# Currently several methods are being used to attempt studies relevant to WDM

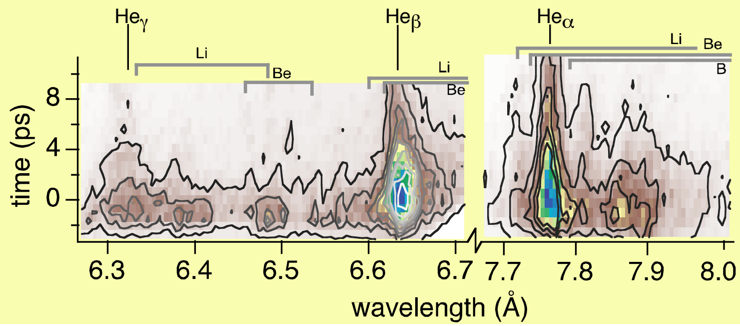
- **Short pulse lasers (SPL)**
  - Heat matter directly; create x-rays to probe matter; create particle beams to heat or probe matter
- ***High energy lasers (e.g., Omega at LLE)**
  - Heat matter directly; create x-rays to heat / probe matter; create shocks
- ***3$^{rd}$ generation sources (ALS, APS, ESRF)**
  - Probe matter; use SPL coupled to beamline to create WDM
- **High explosives (LLNL)**
  - Create matter at ~ 1 eV at near solid density in compression
- **Pulse Power (Z at Sandia)**
  - Can either use x-ray flux to get WDM or indirectly to create shocks

# SPL can create HED for study of exotic atomic states and optical properties

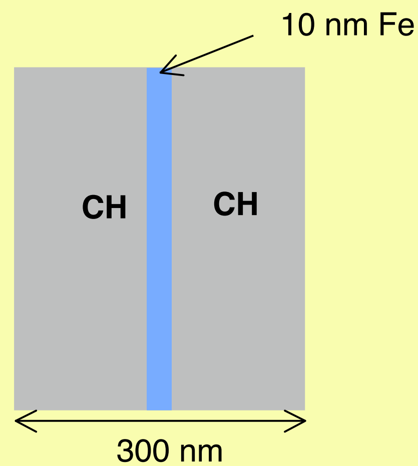
- $10^{17}$ W/cm$^2$ 150 fs pulse hits a 50 nm foil creating exotic state



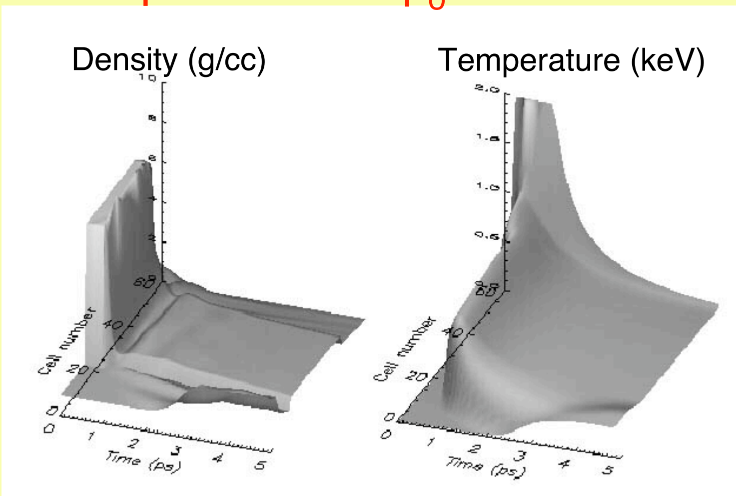

- Spectrum shows existence of continuum of inner-shell states



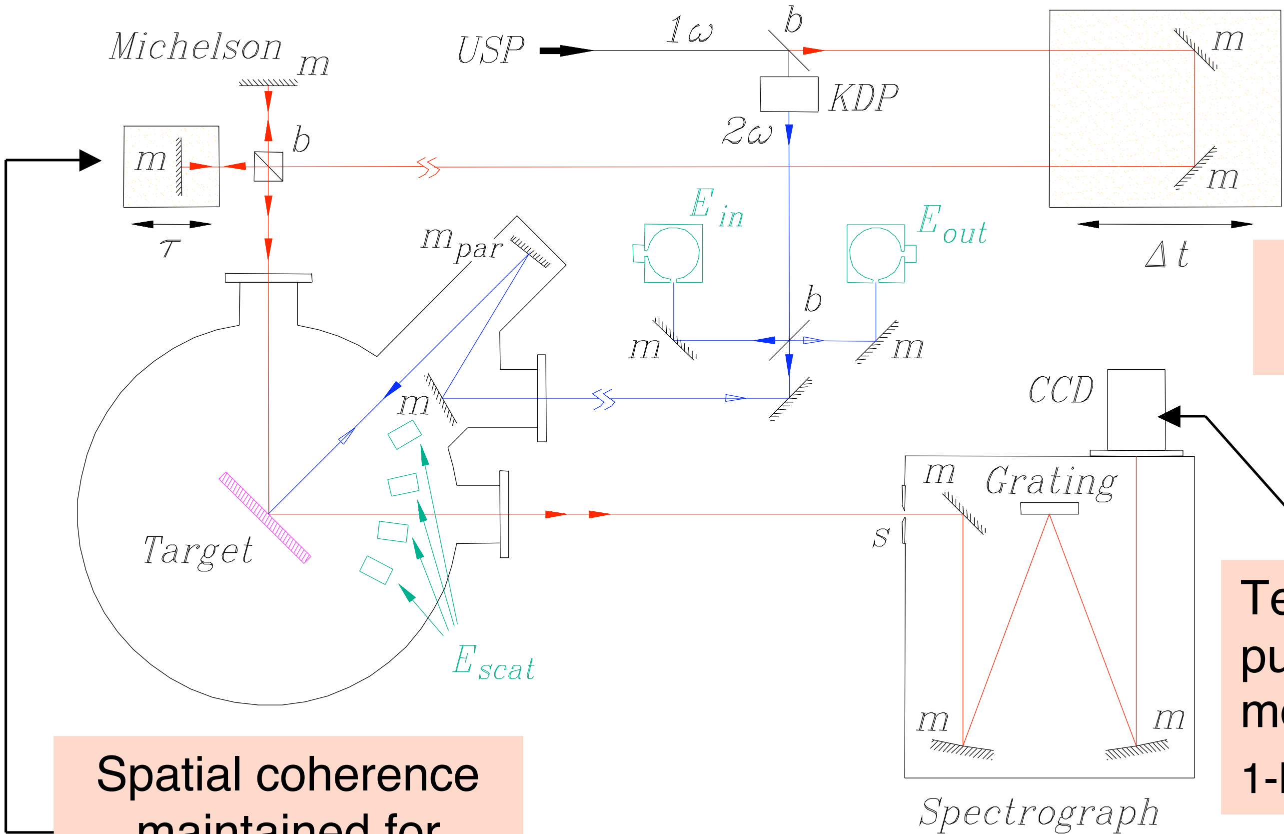

- $10^{17}$ W/cm$^2$ 700 fs pulse hits a CH tamped Fe sample creating uniform HED matter




- At 5 ps Fe is 0.2 $\rho_o$ and 150 eV



# SPL can create WDM in a manner consistent with the study of EOS




Delay between pump and probe

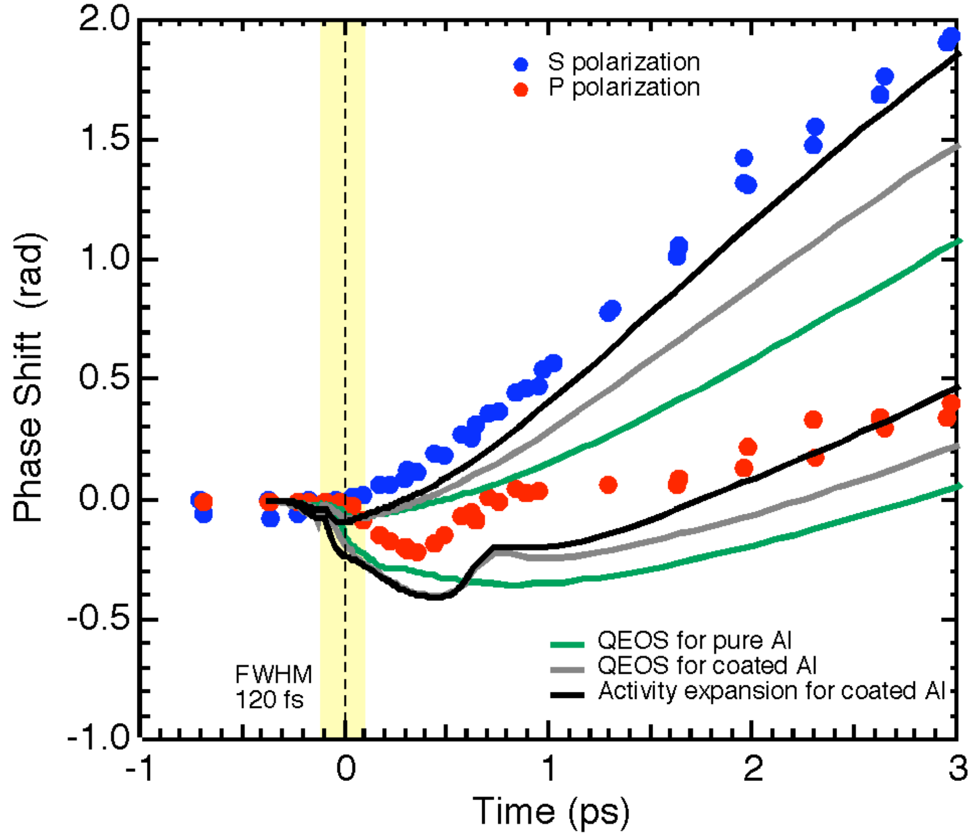
Temporally separated pulses interfere after monochromator → **FDI**

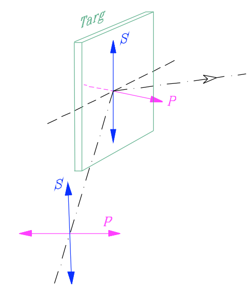
1-D image of probe pulse

Spatial coherence maintained for probe-pulse pair

- Energy balance and FDI measurements provide *insight* into the EOS through hydrodynamic simulations

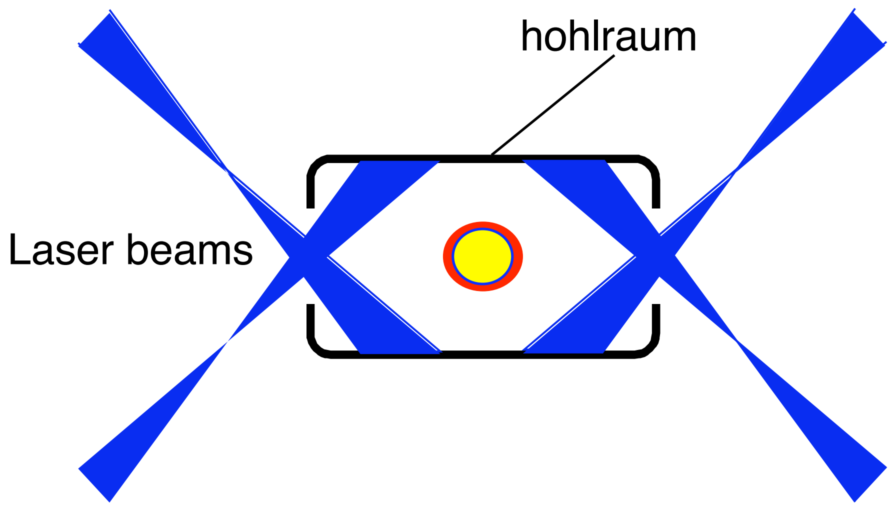
# **Measurements give *insight* into EOS aspects of hydrodynamic simulations**

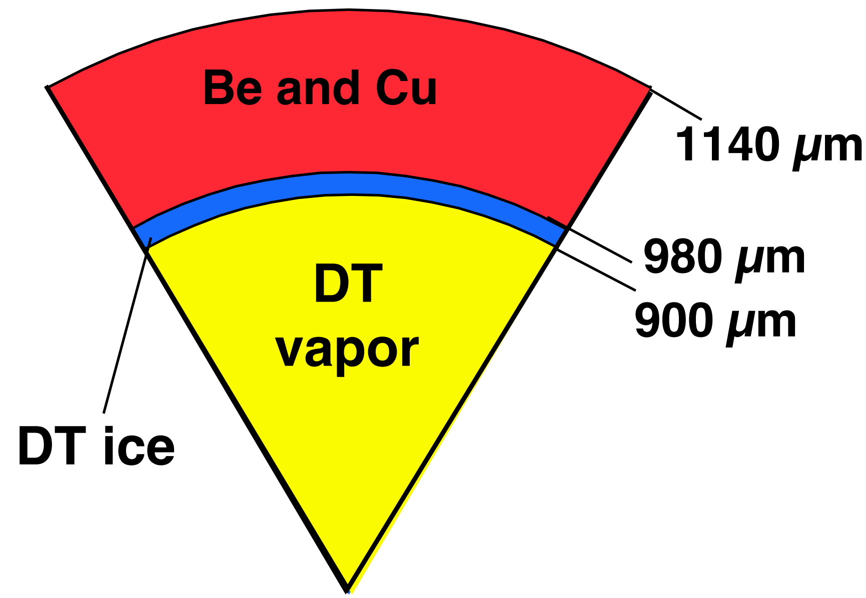


- Data with simulation allow differentiation between:
  1) Pure 4300 Å Al target and one with surface contamination
     - Assayed sample has coating of 26 Å $Al_2O_3$ & 3 Å $CH_2$
  2) Hydro simulations with Thomas-Fermi type or Activity Expansion EOS

# WDM is created in ICF experiments with High Energy lasers



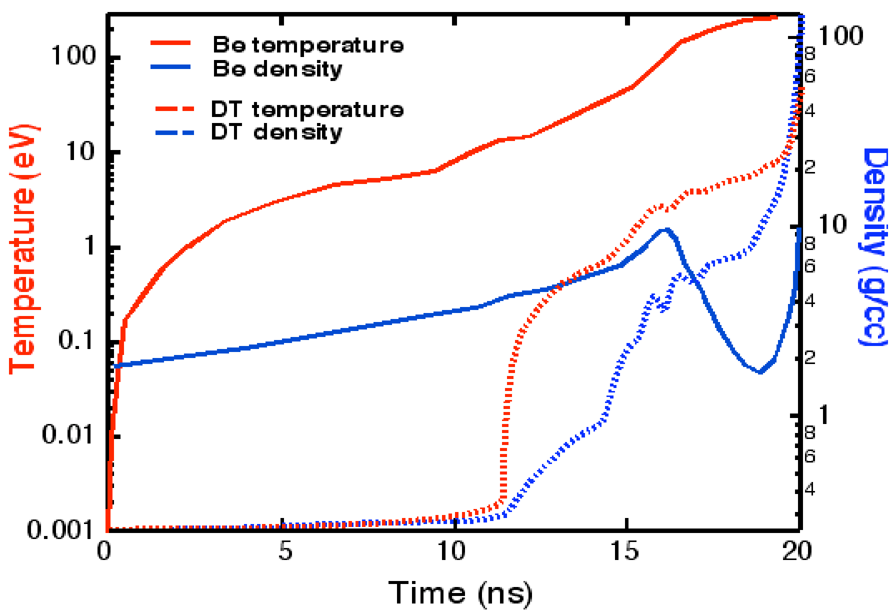




- Laser is focused through hole in holhraum
- Laser impinges on wall creating a plasma
- Wall plasma radiates x-rays
- X-ray are absorbed in the pusher part of sphere
- Heated material drives a shock

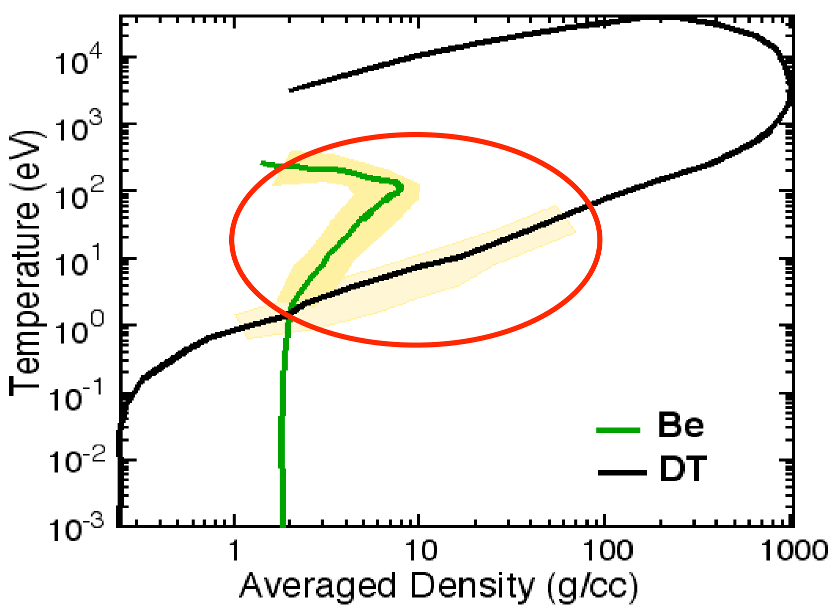
# Designs cause "gentle" compression ⇒ WDM regime is sampled

- The ρ-T paths for Be and DT traverse the WDM regime

• **Time history of Be pusher and DT fuel**




• **ρ-T Track of Be pusher and DT fuel**

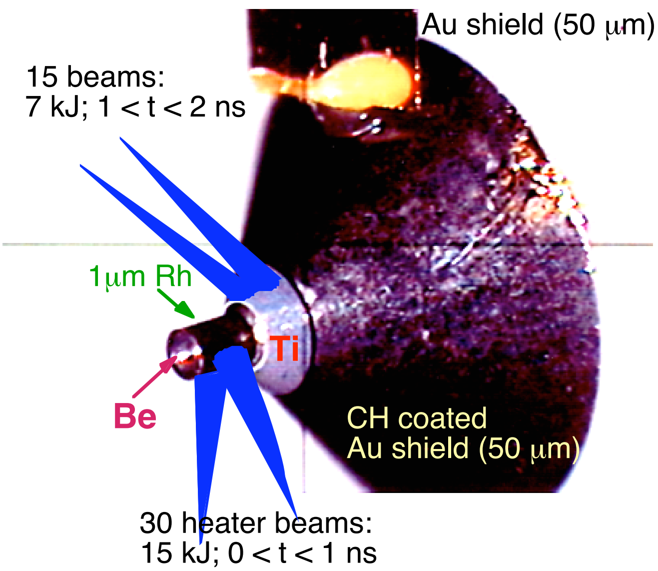



- **DT** EOS may be modified by WDM effects: dissociation, pressure ionization
    - Changes detailed performance of NIF ignition capsules

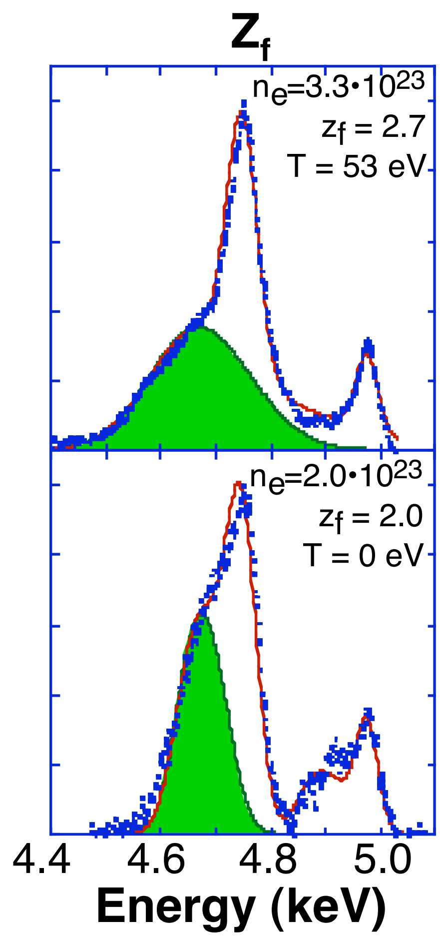
- It is also clear that **Be** will have WDM effects: ionization

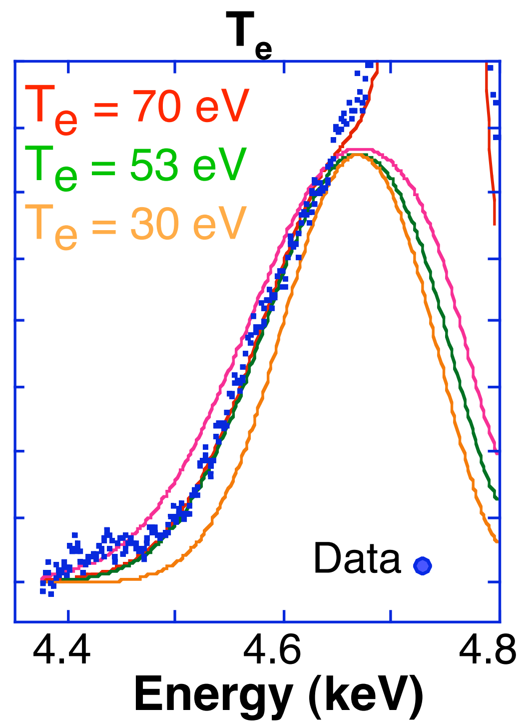
# WDM x-ray Thomson Scattering can be performed on High Energy lasers

- Rh x-ray heated **Be** probed by time delayed Ti x-rays




- Experiment can determine:

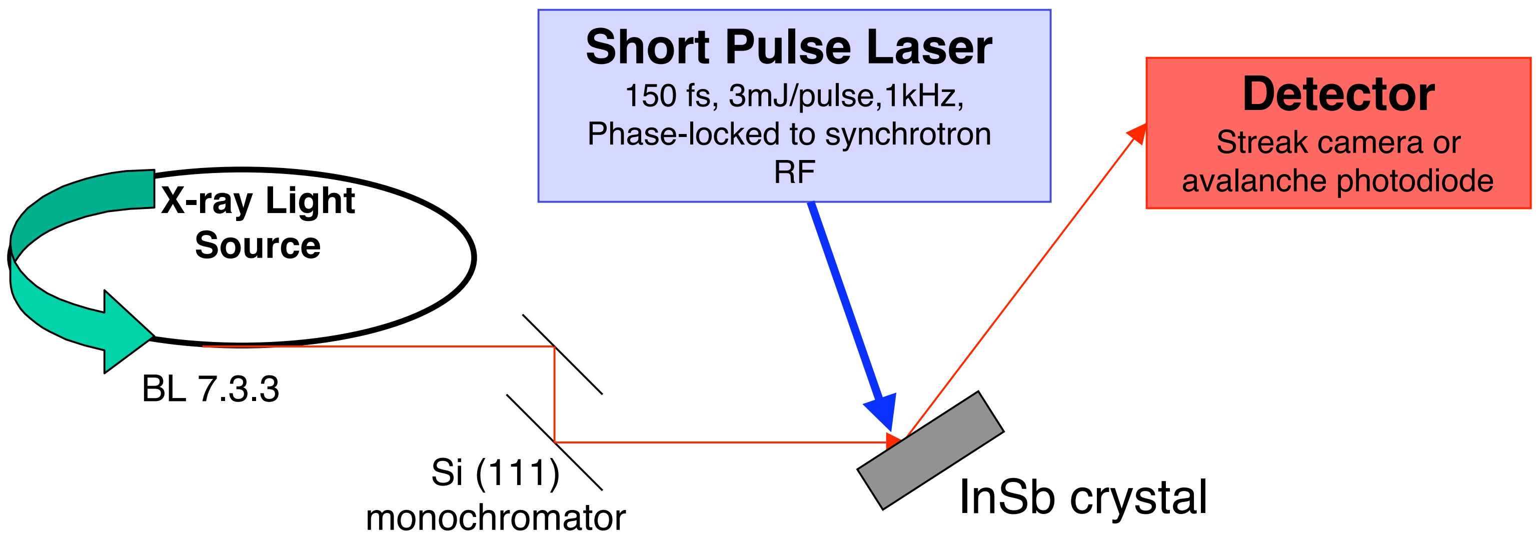



- High energy lasers will be useful at the high temperature end of the WDM regime.

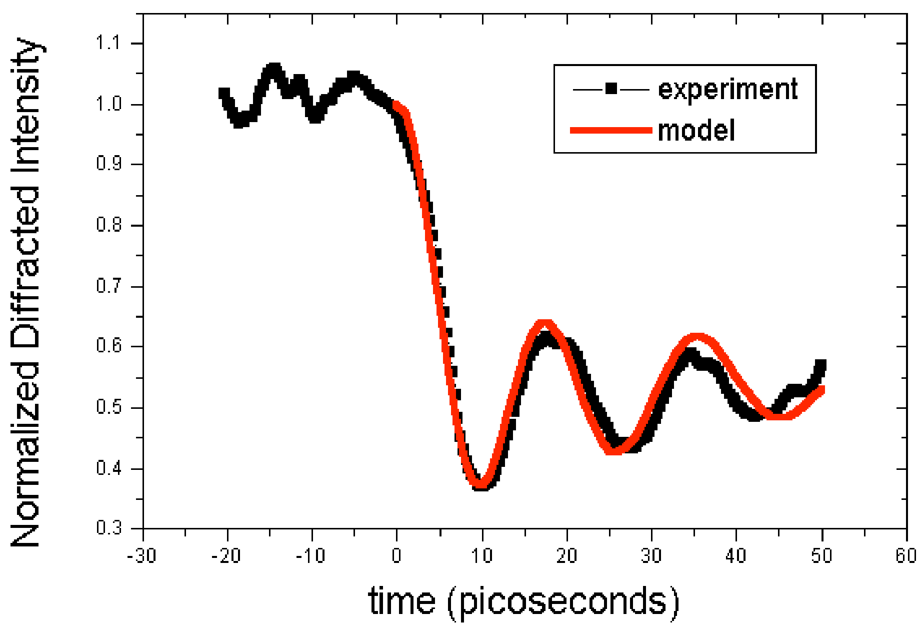
# Short Pulse Lasers coupled to x-ray light source used for WDM studies

- The original set-up was developed to look at rapid structural changes in solid
- Method was extended to look at melting in other material
- Independent study of nanoparticle formation & metal-insulator transitions in supercritical fluids has been started



# ALS WDM experiments lead to an understanding of the heating process

## Phonon Spectroscopy




- The laser heats the crystal
- The crystal planes change their spacing
- The diffraction is thus modulated

- Measurement of phonon dispersion relations under highly non-equilibrium conditions
- Sensitive probe of electron-phonon coupling strengths.
- Structural probe of order-disorder laser-induced phase transitions.

# In the next 5 years there will be few new capabilities for WDM research

- Petawatt laser facility development will provide more places for Short Pulse Laser studies
  - Primary interaction is with surface
    - Can interact directly above critical density $n_c \sim 10^{29}/\lambda(\text{Å})^2\ \text{cm}^{-3}$
  - Protons beams produced by 100 fs SPLs have pulse duration > 5 ps
    - Effort will be to develop quasi-monoenergetic short pulses for WDM production

- Short pulse 3rd generation light sources will allow studies of weakly perturbed WDM on sub-ps times scales
  - Slicing source at ALS at LBNL (2005)
  - Can not perturb matter due to low number of photons per bunch
  - Basically for average brightness experiments

- First 4th generation VUV-FEL will start-up in 2005 at DESY
  - 100 fs, $10^{13}$ photons, initially at 40 eV and eventually at 200 eV energies

# VUV-FEL experiment schedule includes HEDS addressing the WDM regime

- Participation in proposal process included > 100 participants from Europe and North America

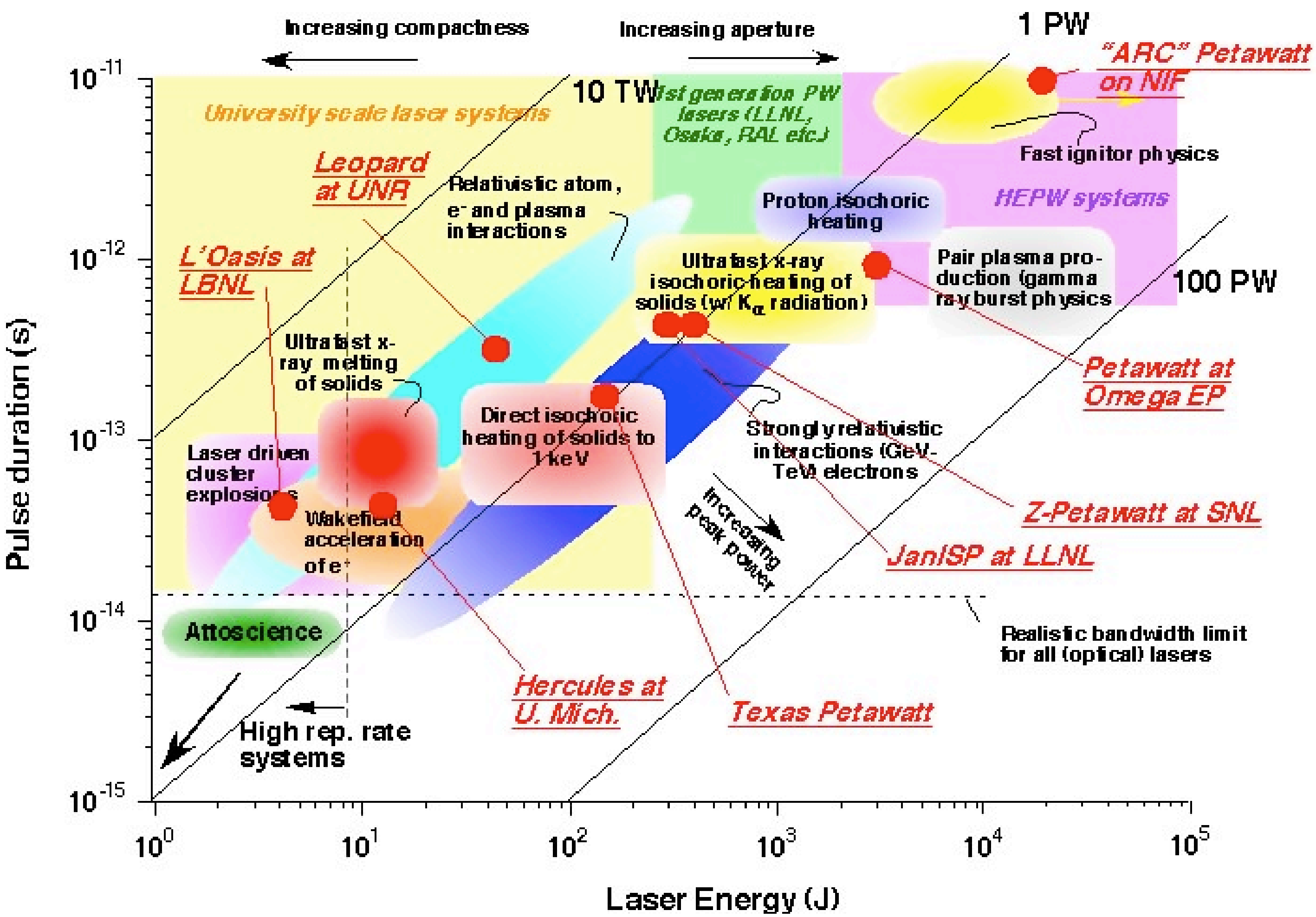
| | Experiment | Brief Description |
|---|---|---|
| Condensed Matter | Warm Dense Matter Creation | Using the FEL to uniformly warm solid density samples |
| | EOS Measurements | Use an optical laser to heat a sample and the FEL to provide a diagnostic of the bulk |
| | Near Edge Absorption | Use an optical laser to heat a solid and the FEL to probe the structural changes |
| | Femtosecond Ablation | Probe the nature of the ablation process on the sub-ps time scale |
| Plasma | Trapped, High $\Gamma$ Plasmas | Use EBIT/laser-cooled trap and probe highly-charged strongly-coupled Coulomb systems |
| | Diagnostic Development | Develop the FEL for Thomson scattering, interferometry, and radiographic imaging |
| | FEL /Gas-Jet Interaction | Create exotic, long-lived highly perturbed electron distribution functions in dense plasmas |
| | FEL / Solid Interactions | Use the FEL directly to create extreme states of matter at high T and $\rho$ |
| | Plasma-Spectroscopic Studies | Use the FEL as a pump to move bound state populations and study radiation redistribution |
| Bio-irelated | Coulomb Explosion | Study Coulomb Explosion process with emphasis on biological imaging problems |
| | Optics Damage | Study structural changes & disintegration processes of solids under FEL irradiation |

# Beyond a 5 year horizon several new facilities will become available

- Petawatt capabilities: several with high energy will be developed (> 2008)
- LCLS@SSRL: the first x-ray FEL with 100 fs pulses of $10^{12}$ photons at energies up to 10 keV, at 120 Hz (2009)
- NIF@LLNL: ~ 2 MJ of energy in ns pulses with low shot rate (2009/2010)
- TESLA@DESY: x-ray FEL with specification similar to LCLS with numerous user end stations is planned (> 2010)
- SIS100@GSI upgrade to an intense heavy ion beam capability (> 2010)

# Petawatt laser effort is broad based; facilities and research are developing

- Higher energy capabilities associated to large scale facilities
- User capabilities need to be developed



# Of the facilities on the "horizon" only the LCLS XFEL is user-oriented

- *Letter of Intent* **for an HEDS experimental station submitted 21 June**
- **HEDS submission separates into Warm Dense Matter (WDM), Hot Dense Matter (HDM), and Diagnostic Development**

| Experiment | Description |
|---|---|
| Warm Dense Matter Creation | Using the XFEL to uniformly warm solid density samples |
| Equation of State Measurements | Heat and probe a solid with an XFEL to provide a diagnostic of material properties |
| Absorption Spectroscopy | Heat a solid with an optical laser or XFEL and XFEL to probe |
| Shock Phenomena | Create shocks with a high-energy lasers and probe with the FEL |
| Surface Studies | Probe ablation/damage process to study structural changes and disintegration |
| FEL / Gas Interaction | Create exotic, long-lived highly perturbed electron distribution functions in dense plasmas |
| FEL / Solid Interaction | Use XFEL directly to create extreme states of matter at high temperature and density |
| Plasma Spectroscopy | Use XFEL as a pump to excite bound state populations |
| Diagnostic Development | Develop Thomson scattering, interferometry, and radiographic imaging |

# Interest in HEDS is growing rapidly and new facilities will play the dominant role

- Two recent National Academy of Science reports have highlighted HEDS:
  - *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century* (National Academies Press, 2003)
  - *Frontiers in High Energy Density Physics - The X-Games of Contemporary Science* (National Academies Press, 2003)
- National Taskforce on HEDS was convened to set priorities and develop coordinated plans
  - Report has been submitted to the sponsors
- HEDS case ***is*** the exactly the “plasma-related” science case already proposed for LCLS, TESLA, and VUV-FEL
  - Heavy Ion Beam case would be straightforward

# Development of a Heavy Ion Beam user capability would be timely

- Heavy ion beams provide a unique method to study HED matter
  - The creation of high pressure in a shockless manner
  - The long time scales and larger volumes obtainable are unique for the WDM regime
  - The heating can be achieved by deposition at the Bragg range or shorter distances
- Repetition rate of 1 Hz coupled to a dedicated user facility would provide an important research tool
  - PW laser coupled to the system could provide:
    - Backlighting
    - Sample preionization for dense plasma related studies
- Five year plan makes heavy ion beams an aggressive competitor with other planned facilities

# Comments on the HIB user Facility

- The form of the experiments can be outlined simply. For example, the heavy ion beam can heat a sample isochorically. Then with measurements of the deposited energy, radiography of the heated volume, and *in situ* probes provided by high-energy laser generated x-rays one can determine the local volumetric expansion and temperatures. Thus the equation of state can be determined. Note in figure one that the area of phase space covered by a single experiment, although it maps out the points along the isentrope as expansion occurs, does not cover the entire space. Indeed, to cover the entire space one needs to make samples of less than solid density, e.g., underdense foams. In this manner one can span a large part of the interesting phase-space with changes of samples but with similar measurement techniques.
- Finally, we note that although the experiment mentioned appears simple it is quite complex. First, the simultaneous measurement of a set of physical parameters in an experiment where all the data must be obtained on each shot necessitates the implementation of a number of diagnostics. This implementation, in turn, requires that the samples be constructed and have metrology performed to ensure that each diagnostic instrument (spectrometers, beam deposition, time resolved radiography, *in situ* scatter and/or absorption measurements) can obtain uncompromised data. This will, in turn, necessitate that shielding of the various components be ensured. Second, the accuracy required for equation of state measurements is highly dependent on the measurement of, for example, the expansion velocities that in turn is dependent on accurate distance versus time diagnostics. In those cases where one uses x-radiography to measure the expansion uniformity of the sample, alignment and diagnostic calibration (e.g., in a streak camera uncertainty in the sweep speed and its linearity) combine to make 10% accuracies difficult to attain. Third, the variation of the heavy ion beam focus, the variation in beam total energy, and the variation in the beam spectrum (here we mean velocity profile) requires that one have a series of reproducible experiments to evaluate a single data point in the EOS. Fourth, the need for reproducibility requires additional pulses. So repetition rates of order minutes or even seconds will be needed to account for the experiment preparations, calibrations, and accelerator variability